Grammatical Processing Using the Mechanisms of Physical Inference

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Abstract

Although there is considerable evidence that humans use the same mechanisms for linguistic and nonlinguistic cognition, the thesis of linguistic modularity will remain plausible so long as well-established formal properties of syntax remain unexplained in terms of domain-general cognitive mechanisms. This paper presents several dualities between the formal structure of syntax and cognitive structures used to represent the physical world. These dualities are used to construct a cognitive model of syntactic parsing that uses only the mechanisms required for infant physical reasoning. The model demonstrates how a formal syntactic constraint, the c-command condition on binding, can be explained by a cognitive process used in physical reasoning. Several consequences for language development and the doctrine of linguistic modularity are considered.

Introduction

Although there is extensive evidence that humans use the same or similar mechanisms for linguistic and nonlinguistic cognition, the precise manner in which nonlinguistic cognitive processes are related to the formal properties of human grammar have yet to be determined.

In the field of linguistic semantics, several researchers have noticed extensive parallels between physical and abstract semantic fields. For example, Jackendoff (1990) has formalized the semantics of many verbs with primitive conceptual structures such as *GO*, *TO*, *FROM*, *PATH*, etc. Leonard Talmy (1985) has shown that semantic fields for psychological, social, argumentative and many other domains involve notions of force dynamics that underlie semantic fields for physical domains. Cognitive psychologists (e.g, Boroditsky, 2001; Spelke & Tsivkin, 2001) have found that the way in which language represents a concept can influence cognition using that concept. Clark's (1996) work culminates a long tradition beginning in the philosophy of language that analyzes language use as a species of social interaction. Bloom (2000) presents evidence that children use cognitive abilities that exist for nonlinguistic purposes to learn the meaning of words.

Some researchers (e.g., Langacker, 1999) have explored the interaction of grammar and nonlinguistic cognition by advancing a "cognitive grammar" research program that views the grammatical structure of sentences as the result of the process which maps linear sequences of words into nonlinear cognitive structures. Although the research has explained many linguistic phenomena, it has not shown in detail how this transformation explains specific syntactic constraints such as the empty-category principle, subjacency and the anaphoric binding principles that occur in some form in most mature formal theories of human syntax. Until these apparently peculiar formal properties are accounted for using general cognitive mechanisms, the thesis that humans use different mechanisms for syntactic and nonlinguistic processing remain plausible.

This paper outlines a mapping of structures in formal grammar to cognitive structures used to represent physical events, shows how to use this mapping to construct a model of human syntactic parsing that uses only the mechanisms of a model of infant physical reasoning and demonstrates how this model explains a universal, putatively innate and language-specific grammatical constraint in terms of domain-general cognitive mechanisms.

Grammatical Structure	Cognitive structure
Word, phrase, sentence	Event
Constituency	Meronomy
Phrase structure constraints	Constraints among (parts of) events
Word/phrase category	Event category
Word/phrase order	Temporal order
Phrase attachment	Event identity
Coreference/binding	Object identity
Traces	Object permanence
Short- and long-distance dependencies	Apparent motion and long paths.

Table 1. Dualities between elements of physical and grammatical structure.

Structural Dualities

The structures of grammar and of naïve physics appear more similar when a verbal utterance is conceived as an event that is composed of a sequence of word utterance subevents. Like physical events, verbal events belong to categories, combine to form larger verbal events and are ordered in relation to other verbal events according to lawful regularities. This section examines these dualities in detail, and shows that many grammatical structures have analogues to nonlinguistic cognitive structures. These dualities are summarized in Table 1.

Notation

In order to explain the mapping between syntactic structure and cognitive structures used to represent the physical world, it will be helpful to use a formal notation for representing physical events. This paper uses a notion based on the notation Cassimatis (2002) uses to present

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14. ABSTRACT
Although there is considerable evidence that humans use the same mechanisms for linguistic and nonlinguistic cognition, the thesis of linguistic modularity will remain plausible so long as well-established formal properties of syntax remain unexplained in terms of domain-general cognitive mechanisms. This paper presents several dualities between the formal structure of syntax and cognitive structures used to represent the physical world. These dualities are used to construct a cognitive model of syntactic parsing that uses only the mechanisms required for infant physical reasoning. The model demonstrates how a formal syntactic constraint, the ccommand condition on binding, can be explained by a cognitive process used in physical reasoning. Several consequences for language development and the doctrine of linguistic modularity are considered.

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problems to his model of physical reasoning. Although there is no claim that the notation resembles the mind's representations for syntactic or physical structure, the next section will show how to use this formalism to present sentences to a model physical reasoning so that the model can use its own representations and processes to infer the syntactic structure of sentences.

In this formalism, events, objects and places have names. Predicates describe attributes on and relations among named entities. For example, an event in which an object, `x`, moves from `p1` to `p2` during the temporal interval, `t`, is indicated with the following propositions: `Category(e, MotionEvent), Agent(e, x), Origin(e, p1), Destination(e, p2), Occurs(e, t)`. Intervals are ordered using Allan's (1983) temporal relations. For example, `Before(t1,t2)` indicates that `t1` finishes before `t2` begins and `Meets(t1, t2)` indicates that `t1` ends precisely when `t2` begins. Category hierarchies are described using subcategory relationships, e.g., `Subcateogry(Fly, MotionEvent)`. `PartOf(e1,e2)` indicates that event `e1` is part of event `e2`. That two names for events, objects or places refer to the same object is indicated using an identity relationship. For example, `Same(o1,o2)` indicates that "o1" and "o2" name the same object. Finally, regularities between physical events can be expressed using material implication. For example, that an unsupported object falls is indicated:

```
Location(o,p1,t1) + Below(p2,p1) +
Empty(p2,t1)
→
Category(e,MotionEvent) + Origin(e,p1)
+ Destination(e,p2) + Occurs(e,t2) +
Meets(t1,t2).
```

With this background, it is now possible to describe several dualities between syntactic and physical structure.

Physical and verbal event perception both have a linear order.

Although human vision has two-dimensional access to a three-dimensional physical world, there is a linear order to human perception. People can attend to only one region of space at a time. Large, complicated and/or spatially distributed visual scenes must be perceived through a series of attentional foci. For example, a person standing between two houses, A and B, can perceive that A is to the left of B by turning to the left, focusing on house A, turning to the right and focusing on house B. Likewise we perceive verbal utterances as a linear sequence of word utterance events.

Further, such multidimensionality as there is in the visual system is not unique to it. Spoken phonemes have a multidimensional character. In most phonological theories phonemes are points in a multi-dimensional vector space with dimensions such as "voiced" or "nasal".

Thus, both perceiving physical scenarios and perceiving spoken utterances involve a linear sequence of foci that each integrate multiple dimensions of information.

Utterances are events.

The philosophical tradition of "speech act theory", (which is psycholinguistically implemented by Clark (1996)), holds that linguistic utterances are actions used to achieve goals. In this way, words are similar to other nonlinguistic actions such as gesturing or tool use. Other people's actions are events we must perceive in order to interpret their intent. Both verbal and nonverbal events occur over temporal intervals. Like nonverbal events, verbal utterances can be executed with various manners (hastily, carefully, loudly, softly).

Thus, the same concepts used to describe physical events can be used to describe verbal utterances. For example, using the present notation, the utterance of the word "dog" at time, `t`, may be represented, `Category(e, dog-utterance), Occurs(e, t)`.

Word order is temporal order.

The temporal order of a set of physical events has important consequences for their ultimate result. For example, pulling a gun's trigger *before* loading it results in a much different event from the pulling its trigger *after* loading it. This is also a fundamental feature of grammar: the result (in terms of its effect on the listener) of uttering "The dog", uttering "bit" and then uttering "John" is much different from the result of uttering "John", "bit" and then "the dog". In our notation, "John bit the dog" is represented as sequence of utterance events:

```
1. Category(e1, JohnUtterance)
   Occurs(e1, t1)
2. Category(e2, BitUtterance)
   Occurs(e2, t2)
   Meets(t1, t2)
Etc.
```

Physical and linguistic events both belong to categories, which exist in hierarchies.

Word and phrase categories are an important component of almost every serious syntactic theory and especially important in some (e.g., Pollard & Sag, 1994). Categories are also an essential part of most every other domain of cognition. The previous subsection demonstrated that the same `Category` predicate that represents the category of a physical event can represent the category of a word or phrase utterance. Likewise, just as physical categories exist in hierarchies (e.g., `Subcategory( RunningEvent, MotionEvent)`, so do verbal and phrasal categories (e.g., `Subcategory(CommonNoun, Noun)` and `Subcategory( TransitiveVerbPhrase, VerbPhrase))`.

Just as the category of a physical event determines which other events it occurs with (e.g., a gun-firing event tends to be preceded by a trigger-pulling event), so does the category of a word or phrase determine the distribution of words and phrases (e.g., transitive verbs are often followed by noun phrases).

Constituency is a meronomic relationship.

Physical events combine into larger events, which themselves can combine into even larger events. Word utterance events combine into phrase utterance events which combine into larger phrase utterance events. Meronomy[1] is thus a feature of both physical and verbal events. Predicates for representing physical event meronomy can capture phrasal constituency. For example, the noun phrase "the dog" can be represented thus:, `Category(e, CommonNounPhrase)`, `Category(e1, Determiner)`, `Occurs(e1, t1)`, `Category(e2, CommonNoun)`, `Occurs(e2, t2)`, `PartOf(e1,e)`, `PartOf(e2,e)`, `Meets(e1,e2)`.

The same notation for expressing physical regularities can be used to represent phrase structure rules and constraints. For example, a rule for a transitive verb's arguments can be expressed thus:

```
Category(verb, TransitiveVerb) +
Occurs(verb, t-verb)
→
Exists(object) + Category(object,
NounPhrase) + Occurs(object, t-object)
+ Before(t-verb, t-object).
```

Coreference and binding are object-identity relationships.

Coreference and binding are perhaps the most obvious identity relationships in language. Consider the following sentence, where "the dog" refers to an object, `d`, "the cat" refers to an object, `c`, and "it" refers to an object, `i`:

The dog chased the cat through the park where it lives.

"it"'s reference is ambiguous. It can refer to the dog (`Same(i,d)`), to the cat (`Same(i,c)`) or to some other object in the conversation or the environment (`Same(i,?)`). In each case, the coreference is just a special kind of identity relationship.

Identity is an extremely widespread and important relationship in everyday physical reasoning. When we lose visual contact with an object because we turn our gaze or because it is occluded and then see a similar object, we must decide whether the sightings are of the same object. Many infant reasoning experiments test for sensitivity to a physical constraint (e.g., continuity (Kestenbaum et al.,

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[1] Meronomy is the study of the relationships of an entity with its parts.

1987) or category persistence (Xu & Carey, 1999)) by testing whether infants are surprised by identities that violate those constraints.

Phrase attachment is an event identity relationship.

The occurrence of a physical event often implies the occurrence of another physical event. For example, when an object resting on shelf falls to the floor (event `f`), there must have been an event (`p`) which pushed the object off the shelf. One can infer the pushing event from the falling event even if the pushing event is not visible. Later, after observing marks left by a cat's claws on the shelf, we can infer a cat walking event (`w`). If this cat walking event occurred near the original location of the object that fell, then the cat walking event might be *identical* to the pushing event, i.e., `Same(p,w)`.

Event identity is an important feature of grammar as well. For example, the existence of a prepositional phrase utterance within a sentence utterance implies the existence of a noun or verb utterance that the prepositional phrase is an argument or adjunct of. For example, in the sentence "John saw the man with the telescope", the "with the telescope" utterance event implies the existence of an utterance event, `pp-head`, which takes "with the telescope" as an argument or adjunct. In this case, `pp-head` might be the "John" or "man" utterance event. More formally, either one of the following propositions might be true: `Same("John",pp-head)` or `Same("the man", pp-head)`. Thus phrase attachment and attachment ambiguity are instances of event identity and uncertainty about event identity.

Traces and Object Permanence

In many clauses, the arguments of a word are spoken. For example, in (1), the subject and object phrases of "eats" are spoken directly before and after it:

(1) [The man] eats [steak].

In some cases, however, the argument of a word is not spoken near it. For example, in (2), the subject noun phrase of "eats" is not adjacent to it. Sentence (3) show this distance is not an obstacle to "eats" requiring its subject to be third-person singular.

(2) The man John said [_ eats [steak]] was wearing a hat.
(3) *The men John said [_ eats [steak]] was wearing a hat.

Thus, even though the subject of "eats" is a "long distance" from it, that subject's character is constrained by or "depends" on "eats". Such relationships are often called "long-distance dependencies". Some grammatical theories posit the existence of a "trace" that is the subject of "eats"

and is left when "the man" is "moved" out of that subject position to another part of the sentence.

Invisible events such as traces and long-distance dependencies are common features of physical inference. For example, if a ball is rolled behind a screen on a flat table and fails to roll out from the other end of the screen, one can posit the existence of a second object behind the screen blocking the first object and make inferences about it (for example, that it is large and massive enough to stop the rolling ball) without ever perceiving the obstacle itself. Thus just as understanding language (depending on one's favorite syntactic theory) requires reasoning about phonetically unrealized phrases, physical event understanding often requires one to reason about events that are not "visually realized", i.e., perceived.

Long-distance dependencies and apparent motion

It was just noted that in (2), the number of the phrase "The man" is constrained by "eats", which is grammatically distant from it. Characterizing and inferring these long-distance dependencies has been a difficult problem for linguistic theorists and designers of sentence parsers for most of modern linguistic history. This contrasts with "short-distance" dependencies which are much simpler. Notice that the subject of "eats" is much closer to and more obvious in (4) than it is in (2).

(2) The man John said [_ eats [steak]] was wearing a hat.
(4) The steak John said [the man eats _] was tender.

A rough way of characterizing the difference between the two sentences is that the immediate proximity of "eats" to its subject makes their relationship much more obvious.

In the case of physical inference, the phenomenon of object permanence is an example of proximity (in space and time) making an identity relationship much more obvious than the identity of two objects perceived over a long-distance. When people see an object at a particular place and time and then in a fraction of a second see an object with a similar appearance, the two object sightings are perceived as the "apparent motion" of a single object. When the distance between the two objects in space and time is much larger, the identity is no longer obvious. For example, when a red Toyota drives into a crowded parking deck and a red Toyota emerges an hour later, the two car sightings might or might not be of the same car. The identity is not so obvious. Thus, long-distance dependencies and the problems they pose are a common feature of linguistic as well as physical events.

Infant physical reasoning mechanisms are sufficient to infer grammatical structure.

The dualities between physical and grammatical structure suggest that mechanisms for inferring the physical structure of the world might be useful for inferring the grammatical

structure of an utterance. This section presents a model of syntactic understanding that is based on Cassimatis' (2002) model of infant physical reasoning. The model accounts for a wide variety of syntactic phenomena, including gapped constructions, long-distance dependencies and binding principles, using only the mechanisms included in the physical reasoning model.

Since the central argument of this paper is that human physical reasoning mechanisms, whatever they are ultimately found to be, are sufficient to parse syntactic structure, this paper has only discussed how to formulate parsing problems as physical reasoning problems and does not discuss in any detail the mechanisms of the physical reasoning model.

Polyscheme contains several modules, called *specialists*, for representing aspects of the physical world. Grammatical knowledge was added to Polyscheme using the representations of these specialists. For example, the category hierarchy (strictly speaking, a multi-tree) of Polyscheme's category specialist was used to represent lexical and phrasal category relationships; its temporal specialist was used to represent word order; its meronomic specialist was used to represent phrasal constituency and Polyscheme's physical constraint specialist was used to represent phrase structure constraints. No modifications of Polyscheme representations were needed to represent grammatical knowledge.

Physical problems are presented to Polyscheme using the formal language outlined in the last section. The structural dualities described in that section enable sentences to be presented to Polyscheme so that it can use its physical reasoning mechanisms to parse them. For example, the sentence, "The dog John bought bit him", is represented by a series of propositions, `Category(w1, TheUtterance)` `Occurs(w1, t1)`, `Category(w2, DogUtterance)` `Occurs(w2, t2)`, `Meets(t1,t2)`, etc.

Upon receiving sentences in this format Polyscheme (using its mechanisms for resolving uncertainties) infers that the event w2 is a `NounUtteranceEvent` and that it should be preceded by an event, `dogDeterminer`, that is a `DeterminerUtterance` event. Polyscheme's inference that "the" is the determiner of "dog" is represented by the proposition: `Same(w1,dogDeterminer)`, which indicates that the determiner event implied by "dog" is "the". Polyscheme's parse of an utterance is represented by a set of such propositions. They represent the identity of heads, arguments and adjuncts implied by words and phrases in the utterance (e.g., `dogDeterminer`) to the actual spoken words or phrases perceived (e.g., "the"). These propositions constitute a complete description of the syntactic structure of a sentence. Figure 1 illustrates the parse of the sentence, "The dog John bought bit him".

The crucial point is that once a sentence is represented in Polyscheme's input format, *only the mechanisms needed for physical inference are necessary to infer the grammatical structure of the sentence.*
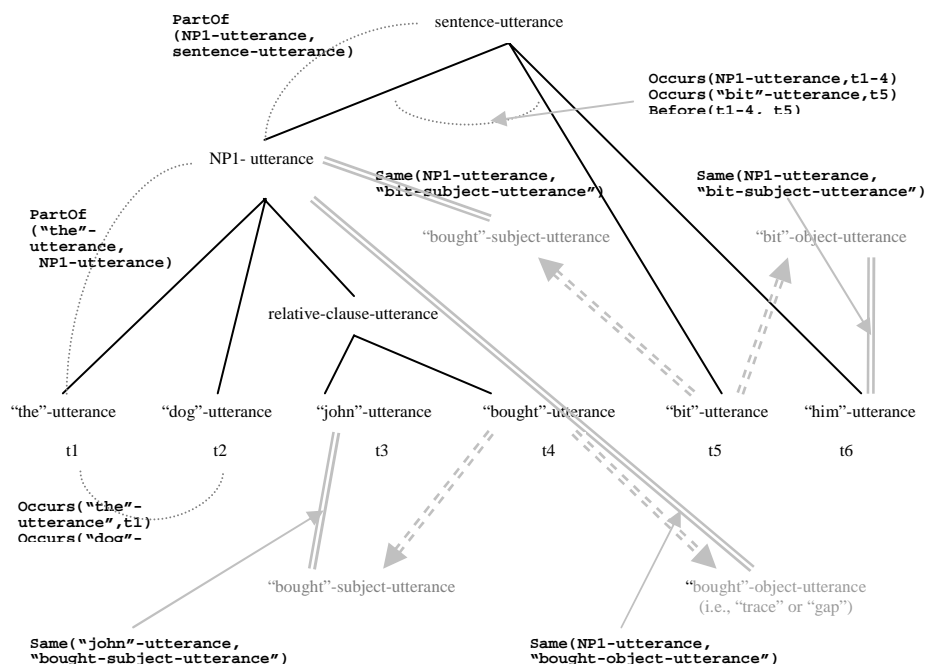
Figure 1. The syntactic structure of a sentence represented using concepts from infant physical reasoning.

Domain-general cognitive processes can enforce grammatical constraints.

The existence of several language universal constraints on syntactic structure is perhaps the most apparently unique feature of syntactic theory. Since they appear so peculiar to language, these constraints lend creditability to the thesis of linguistic modularity. This section argues that a supposed language-specific constraint, the c-command condition on binding, can be represented using the same cognitive structures used to represent physical events and that the cognitive processes used in the Polyscheme physical reasoning model from the last section explain how parsing obeys such constraints.

Radford (1997) formulates the c-command condition on binding thus: *A bound constituent must be c-commanded by an appropriate antecedent.* He defines c-command by stating that *A node X c-commands Y if the mother of X dominates Y, X ≠ Y and neither dominates the other*.

C-command is a constituency relationship and can therefore be reformulated using the notation of section 2:

> *X **c-commands** Y if* PartOf(X,Z) *and there is no* X' *such that* PartOf(X,X') *and* PartOf(X',Z) *(i.e.,"Z is the mother of X");* PartOf(Y,Z) *("Z dominates Y");* Same(X,Y) *is false ("X≠Y"); and*

PartOf(X,Y) *and* PartOf(Y,X) *are both false* ("neither dominates the other").

Having thus reformulated c-command as a meronomic relationship, it is possible explain how a cognitive process called *part inhibition*, which Polyscheme uses for physical reasoning, forces Polyscheme to observe the c-command condition on binding when parsing sentences.

In most physical interactions, a moving object "stays together". The parts of the object move together with the rest of the whole object. Spelke (1990) has termed this the "Cohesion Principle". This principle implies that people tracking the motion of an object composed of many smaller objects need only track the compound object. Its component objects will be wherever the whole object is. This makes, for example, the task of tracking one object composed of seven smaller objects generally much less than seven times more difficult than tracking one simple object. Thus, the Cohesion Principle supports the practice of paying more attention to a whole objects than to its parts. Markman (1989) found evidence that children do this when learning words. In Polyscheme, this attention preference can be implemented with "part inhibition":

> *When entities* e_1, …, e_n, *are learned to be part of a larger entity,* E, *inhibit each of the* e_i.

When active during syntactic parsing in Polyscheme, part inhibition suppresses the activation of phrases that are forbidden antecedents under the c-command condition of binding. This is illustrated for the sentence, "The doctor Mary met at Bill's house likes herself". Notice that by the time processing reaches "herself", the model will have inferred that several noun phrases are constituents (directly or indirectly) of other noun phrases. In particular:

- PartOf("house", "Bill's house").
- PartOf("Bill's house", "The doctor Mary met at Bill's house").
- PartOf("Mary", "The doctor Mary met at Bill's house").

Part inhibition will therefore inhibit (and hence make them less likely binding targets) "house", "Bill's house" and "Mary" because they are each part of at least one larger utterance event. The following rewrite of the sentence shows these inhibited noun phrases in light gray:

[The doctor [Mary] met at [[Bill]'s house]] likes herself.

This example demonstrates that a single cognitive process (meronomic inhibition) can help syntactic inference conform to a grammatical constraint (on anaphoric binding) and on a physical constraint (on object motion). Although this is only one of many language-universal syntactic constraints, it raises the possibility that other constraints can be so treated.

Conclusions and future directions

Considerable work remains to establish that the mechanisms underlying physical reasoning also support syntactic parsing and that the model this paper presents is on the right track. The model must be extended to account for more languages and more grammatical phenomena, especially accounts of other universal syntactic constraints. The influence of mechanisms such as part inhibition on the observance of syntactic constraints must also be empirically confirmed. To the extent that the proposed dualities between cognitive structures and processes involved in inferring the structure of physical events and the syntactic structure of sentences are real, several important consequences follow.

First, the ability of a cognitive process such as part inhibition on help inference conform both to syntactic binding conditions and to the cohesion constraint on object motion is relevant to arguments for the existence of innate linguistic knowledge. These arguments (e.g., Chomsky, 1975) assert that children's early linguistic experience is too poor for them to learn these grammatical constraints and conclude that the constraints must therefore be part of some innate linguistic knowledge. This paper raises the possibility that these constraints are the linguistic manifestations of cognitive processes involved in cognition generally. These processes themselves may be innate or children may develop them as they learn to interact with their physical environment. In either case, since children's

physical experience is so much richer than their early linguistic experience, this and many issues surrounding a putatively innate language faculty cannot therefore be resolved through *a priori* learnability arguments alone.

Finally, this work raises two methodological opportunities. First, since many other arguments in developmental psychology are also of the form, "behavior B implies knowledge or mechanism X", cognitive models which display B without X can potentially falsify those claims. Second, if the same mechanisms underlie physical reasoning and syntactic parsing, then corresponding to each language universal syntactic constraint should be a cognitive mechanism that supports the observance of this constraint in the same way that supports binding constraints. This suggests the potential for the theoretical posits of syntactic theory to be used as clues for the discovery of cognitive processes and *visa versa*.

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